

**GUIDED WAVE ELECTROOPTIC AND ACOUSTOOPTIC  
TUNABLE FILTER APPARATUS AND METHOD**

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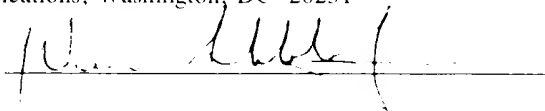
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"Express Mail" Mailing label number EL533564516US

Date of Deposit: December 14, 2000

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A handwritten signature in dark ink, appearing to read "J. Nevin Shaffer, Jr.", is written over a horizontal line.

# GUIDED WAVE ELECTROOPTIC AND ACOUSTOOPTIC TUNABLE FILTER APPARATUS AND METHOD

The Applicant hereby claims the benefit of the earlier filing date of December 23, 1999, of Provisional Application Serial No. 60/173,018, under 35 U.S.C. §119(e).

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## BACKGROUND OF THE INVENTION

This invention relates to an apparatus and method for the selection of light of one optical frequency or wavelength channel from a multiplicity of channels or optical frequencies being transmitted in an optical fiber or optical waveguide. The invention can also be used to efficiently combine light waves of different frequencies.

Filter technology for wavelength division multiplexing (WDM) is one of the most active research and development topics in the optical fiber telecommunications field. A number of guided wave filter approaches are at various stages of development, including the fiber Bragg grating, fiber Fabry-Perot, asymmetrical Mach Zehnder interferometer (MZI),

1 waveguide grating router (WGR), acoustooptic tunable filter (AOTF), and electrooptic tunable  
2 filter (EOTF).

3 Of these technologies, only the AOTF and EOTF can be tuned from one channel to  
4 another at near-microsecond (for the AOTF) or sub-microsecond (for the EOTF) speeds  
5 needed for fast packet-switched networks. As illustrated in Figs. 1 and 2, conventional, prior  
6 art, schemes for implementing the AOTF and EOTF have several features in common. Both  
7 are fabricated in ferroelectric insulating substrates such as lithium niobate, and make use of a  
8 four-port MZI structure formed from waveguides which are single mode for both horizontally  
9 polarized light (TE) and vertically polarized light (TM). Both filters make use of phase-  
10 matched polarization conversion in the arms of the MZI, and ideally their performance is  
11 independent of the incident polarization state. Another common feature of the conventional  
12 AOTF and EOTF designs is that they both use polarizing beam splitters (PBSs), optical circuit  
13 elements which have proven difficult to fabricate with the high polarization extinction ratios  
14 needed to meet filter requirements.

15 A prior art four-port beam splitter is illustrated in Fig. 3. Light incident in port 1 will,  
16 in general, be split between output port 1 (straight through port) and output port 2 (crossover  
17 port). The requirement for a PBS is that, for  $i, j = 1, 2$ :  $(f_{TE})_{ii} = 1$ ;  $(f_{TE})_{ij} = 0$ ,  $j \neq i$ ;  $(f_{TM})_{ii} =$   
18  $0$ ;  $(f_{TM})_{ij} = 1$ ,  $j \neq i$ , where  $(f_P)_{ij}$  is the fraction of the power in input port  $i$  which couples to  
19 output port  $j$  for polarization  $P$ . (It should be noted that an alternative PBS design is obtained  
20 by reversing "TE" and "TM" in these expressions). As more fully disclosed hereafter,  
21 Applicants' invention is directed to new AOTF and EOTF configurations which allow for an

1 additional degree of freedom in beam splitter characteristics and which are, therefore, much  
2 easier to fabricate than the conventional filters.

### 4 **Principles of Operation of Conventional AOTFs and EOTFs**

5 The prior art AOTF depicted in Fig. 1 makes use of the strain-optic effect from a  
6 traveling acoustic wave to produce polarization conversion in the two arms of the MZI  
7 structure, which is fabricated on a  $\text{LiNbO}_3$  substrate. The conversion is very efficient at the  
8 optical frequency  $\nu_j$  for which a phase matching condition is satisfied, such that the acoustic  
9 wavelength exactly matches the TE - TM polarization beat length in the waveguide. At other  
10 optical frequencies for which the phase matching condition is not satisfied, little polarization  
11 conversion occurs. Horizontally polarized (TE) light incident on the filter at a frequency  $\nu_i$  is  
12 directed by the first PBS into its straight through output port - the upper waveguide in the  
13 Mach-Zehnder. If the polarization is not converted in that waveguide ( $i \neq j$ ), the light incident  
14 on the second PBS is also directed to its straight through output port, which is the upper output  
15 port of the filter. If the polarization is converted ( $i = j$ ), the light incident on the second beam  
16 splitter emerges from its crossover port, which is the filter's lower output port.

17 On the other hand, vertically polarized (TM) light incident on the filter at a frequency  
18  $\nu_i$  is directed by the first PBS into its crossover output port, the lower waveguide in the MZI.  
19 If the polarization is not converted in that waveguide ( $i \neq j$ ), the light incident on the second  
20 PBS is also directed to its crossover port, the filter's upper output port. If the polarization is  
21 converted ( $i = j$ ), the light incident on the second beam splitter emerges from its straight  
22 through output port, which is the filter's lower output port. Thus, for either polarization TE

1 or TM, the light at the selected frequency  $\nu_j$  emerges from the lower output port of the filter,  
2 and all other frequencies exit via the upper output port. Tuning of the filter to change the  
3 selected optical frequency is accomplished by changing the acoustic frequency.

4 Conceptually, the conventional EOTF differs from the AOTF in two respects: both the  
5 polarization coupling mechanism and the tuning method are different. In the EOTF illustrated  
6 in Fig.2, tuning is accomplished by an applied voltage  $V_j$  which changes the waveguide  
7 birefringence and hence the optical frequency  $\nu_j$  for which phase matching occurs. A spatially  
8 periodic strain-inducing film causes polarization coupling via the strain-optic effect. In other  
9 EOTF designs, a spatially periodic electric field produced by an interdigital electrode structure  
10 induces the polarization coupling via the electrooptic effect.

### 11 12 **Beam Splitter Description**

13 Performance of the four-port beam splitter of Fig. 3 is described by the expression  
14

$$15 \quad O_p = C_p I_p, \quad (1)$$

16  
17 with

$$18 \quad I_p = \begin{bmatrix} (I_p)_1 \\ (I_p)_2 \end{bmatrix}, \quad (2)$$

$$O_P = \begin{bmatrix} (O_P)_1 \\ (O_P)_2 \end{bmatrix}, \quad (3)$$

and

$$C_P = \begin{bmatrix} (c_P)_{11} & (c_P)_{12} \\ (c_P)_{12} & (c_P)_{11} \end{bmatrix} \quad (4)$$

In these expressions  $P$  represents the polarization (TE or TM),  $(I_p)_i$  is the input electric field amplitude in port  $i$  ( $i = 1, 2$ ),  $(O_p)_i$  is the corresponding output electric field amplitude, and the coupling coefficients are

$$(c_P)_{11} = \cos(\kappa_P L) \quad (5)$$

$$(c_P)_{12} = i \sin(\kappa_P L), \quad (6)$$

with  $\kappa_P$  the interwaveguide coupling coefficient and  $L$  the effective length of the coupling region. The analysis neglects loss and assumes that the coupled waveguides are identical and support a single mode for each polarization, but that in general the mode field patterns and hence the coupling coefficients are different for the two polarizations.

1 For a polarizing beam splitter with TE polarization directed in the straight through path  
2 and TM polarization crossing over, the coupling coefficients must satisfy these conditions:  
3  $(c_{TE})_{11} = 1, (c_{TE})_{12} = 0; (c_{TM})_{11} = 0; (c_{TM})_{12} = 1$ . For these relations to hold,  $\kappa_{TM}L = (2m_1 -$   
4  $1)\pi/2, \kappa_{TE}L = m_2\pi$ , with  $m_1$  and  $m_2$  positive integers. Thus, constraints on both coupling  
5 coefficients must be met simultaneously to satisfy the requirements for a PBS. Furthermore, from  
6 a practical standpoint it is desirable to make the coupler as short as possible, implying small values  
7 of  $m_1$  and  $m_2$ . For  $m_1 = m_2 = 1$ , for example,  $\kappa_{TM}L = \pi/2$  and  $\kappa_{TE}L = \pi$ , so  $\kappa_{TE} = 2\kappa_{TM}$ . This  
8 implies a considerably broader mode profile for the TE mode than for the TM mode, which is  
9 undesirable from the standpoint of mode matching to an optical fiber.

#### 11 SHORT STATEMENT OF THE INVENTION

12 Accordingly, as opposed to those now known in the industry, the AOTF and EOTF  
13 apparatus and methods of the present invention do not require polarizing beam splitters. Further,  
14 because the invention provides an additional degree of freedom in achieving the required beam  
15 splitter performance, it is much easier to fabricate than prior art AOTFs and EOTFs which make  
16 use of polarizing beam splitters. In particular, a guided wave tunable filter of the present  
17 invention includes, in a preferred embodiment, two 3-port Y-branch beam splitters connected to  
18 form two spaced apart waveguides between said beam splitters, with an input port and an output  
19 port. The waveguides include an optical path difference of half a wavelength and polarization  
20 coupling regions in the two waveguides are displaced by half the spacial period of a perturbation  
21 responsible for coupling. Both acoustooptic and electrooptic tunable filters of the two port design

1 are disclosed. Additionally, in a preferred embodiment, a four port AOTF and a four port EOTF  
2 are also disclosed.

### 3 4 BRIEF DESCRIPTION OF THE DRAWINGS

5 Other objects, features and advantages of the present invention will become more fully  
6 apparent from the following detailed description of the preferred embodiment, the claims and the  
7 accompanying drawings in which:

8 FIGURE 1 is an illustration of a Prior Art AOTF;

9 FIGURE 2 is an illustration of a Prior Art EOTF;

10 FIGURE 3 is an illustration of a Prior Art four-port beam splitter;

11 FIGURE 4 is an illustration of a preferred embodiment of a four-port AOTF of the present  
12 invention;

13 FIGURE 5 is an illustration of a preferred embodiment of a four-port EOTF of the present  
14 invention;

15 FIGURE 6 is an illustration of a preferred embodiment of a two-port AOTF of the present  
16 invention; and

17 FIGURE 7 is an illustration of a preferred embodiment of a two-port EOTF of the present  
18 invention.

### 19 20 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

21 The preferred embodiment of the present invention is illustrated by way of example in  
22 FIGURES 4-7. Filter designs introduced here for the purpose of relaxing constraints on beam



splitter characteristics are illustrated in Figs. 4 and 5. In general, these differ from the conventional designs of prior art Figs. 1 and 2 in the following respects: (1) polarizing beam splitters are not required, (2) the optical path difference for the waveguides between the beam splitters for both polarizations is a half-wavelength, or an odd integral multiple thereof, and (3) the relative positions of the polarization coupling regions in the two waveguides are displaced in the propagation direction by half the spatial period of the perturbation responsible for the coupling.

To analyze these new filter designs, the case of P polarization input with no polarization conversion is considered first. The transfer matrix for the filter is given by

$$O_P = C_P M_\pi C_P I_P \quad (7)$$

with  $M_\pi$  the matrix which describes the pi-radian relative phase shift due to the half-wavelength path difference, given by

$$M_\pi = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad (8)$$

Evaluating the matrix product in eq. (7) yields

$$O_P = \begin{bmatrix} (c_P)_{11}^2 - (c_P)_{12}^2 & 0 \\ 0 & (c_P)_{12}^2 - (c_P)_{11}^2 \end{bmatrix} I_P \quad (9)$$

1 It follows from equations (5) and (6) that

$$O_P = M_{\pi} I_P \quad (10)$$

2  
3  
4  
5 Since  $M_{\pi}$  is diagonal, all of the power incident in port  $i$  in either polarization exits from output  
6 port  $i$ . This represents the case of the non-selected frequencies for which no polarization  
7 conversion occurs in the waveguides. Power incident in port  $i$  couples part of the way to port  $j$   
8 in the first coupler, but then couples back to port  $i$  in the second coupler.

9 For the case that polarization conversion occurs between incident polarization  $P$  and output  
10 polarization  $P'$ , the transfer matrix is given by

$$O_{P'} = C_{P'} M_{\pi} M_{\pi} C_P I_P. \quad (11)$$

11  
12  
13  
14  
15 In this case, the light passes through the first coupler with polarization  $P$  and through the second  
16 coupler with polarization  $P'$ . The second factor  $M_{\pi}$  in eq. (11) accounts for the relative  
17 displacement of the coupling regions in the waveguides by half the spatial period of the perturbation  
18 responsible for the polarization coupling. Since  $M_{\pi} M_{\pi}$  equals the unitary matrix, eq. (11)  
19 immediately simplifies to

$$O_{P'} = C_{P'} C_P I_P. \quad (12)$$

From eqs. (4)- (6), and making use of the trigonometric relations  $\cos (A+B) = \cos A \cos B - \sin A \sin B$  and  $\sin(A+B) = \sin A \cos B + \cos A \sin B$ , it follows that

$$C_{P'} C_P = \begin{bmatrix} \cos(\Theta) & i \sin(\Theta) \\ i \sin(\Theta) & \cos(\Theta) \end{bmatrix} \quad (13)$$

with

$$\Theta = \kappa_{TE} L + \kappa_{TM} L. \quad (14)$$

where "TE" and "TM" have replaced "P" and "P' ". The condition for complete power crossover to occur, such that all power incident in port i exits via output port j, is  $\cos \Theta = 0$ , or  $\Theta = (2m_3 - 1)\pi/2$ , with  $m_3$  a positive integer. For the shortest couplers, with  $m_3 = 1$ ,  $\Theta = \pi/2$ . It follows from eqs. (5), (6), and (14) that a condition for complete power crossover can be written

$$(f_{TE})_{ji} + (f_{TM})_{ji} = 1 \quad (15)$$

for  $i = 1$  or  $2$ , where  $(f_P)_{ji}$  is the fraction of incident power with polarization P incident on the coupler in port j which exits via port i, given by

$$(f_p)_{ij} = \frac{1}{2} c_p^{-1} \omega_{ij}^2 \quad (16)$$

### ALTERNATIVES

As illustrated in Figs. 4 and 5, the disclosed filters of the present invention perform the "drop" function of removing one optical wavelength or frequency and allowing all others to propagate. These same filters can perform the "add" function, as illustrated by the same Figs. 4 and 5 with the direction of the light propagation (as indicated by arrows in the diagrams) reversed.

Tuning of the apparatus shown in Figs. 4 and 5 enables the achievement of optimum performance in various circumstances. In every circumstance, it is required that the optical path difference in the MZI equal an odd integral multiple of a half wavelength, which is satisfied by a physical path difference of 350 nm in LiNbO<sub>3</sub> at 1.53 μm wavelength for extraordinary polarization. For this path difference, a phase error of about 0.1 rad results for the ordinary polarization due to the large substrate birefringence. This error is readily compensated by a section of waveguide outside the polarization conversion region in which the birefringence is altered by either a strain-inducing film or an electrooptic interaction.

It should also be noted that, in the case of the AOTF, the relative displacement of the polarization coupling regions in the two waveguides as a fraction of the polarization beat length in the waveguides changes with tuning of acoustic frequency. The effect is significant, amounting to about ± 0.15 rad for tuning of the optical frequency by ± 1 THz, but is correctable through the use of a phased array or tilted finger chirped acoustic transducer design in which the propagation direction of the acoustic wave changes in angle linearly with acoustic frequency.

1       The condition given in eq. (15), which must be satisfied by couplers for the new filter  
2 designs of the present invention, can readily be achieved in practice. For example, in a preferred  
3 embodiment, the effective coupling length  $L$  and the waveguide width are fixed a priori, with  
4 coupling strengths  $\kappa_p$  for the two polarizations determined by an appropriate choice of waveguide  
5 separation. The  $\kappa_p$  values are both monotonically decreasing functions of waveguide separation.  
6 By measuring  $(f_{TE})_{ii}$  and  $(f_{TM})_{ii}$  for test coupler patterns with different waveguide separations, a  
7 separation for which eq. (15) is satisfied can readily be determined.

8       Since the filters of the present invention will be used in fiber optic systems, it is desirable  
9 to match the mode electric field patterns for both polarizations as closely as possible to a single  
10 mode fiber field pattern. This is a consideration in determining the waveguide fabrication  
11 procedure. For example, if the waveguides are formed by Ti diffusion in  $\text{LiNbO}_3$ , the diffusion  
12 time and temperature should be chosen with this in mind. Even so, it is expected that there would  
13 be significant differences in the TE and TM mode profiles, which would be reflected in the  
14 coupling constant values  $\kappa_{TE}$  and  $\kappa_{TM}$ . These differences, however, do not pose a problem in  
15 implementing the new filter designs of the present invention.

16       By contrast, two constraints must be satisfied simultaneously for the PBSs used in  
17 conventional tunable filter designs, making it much more difficult to achieve the needed coupler  
18 performance. Thus, the invention considers a PBS optimization procedure in which the waveguide  
19 width and coupling length are fixed and the waveguide separation is varied. A waveguide  
20 separation for which complete crossover is achieved for TE polarization would not, in general,  
21 also meet the companion requirement of providing complete straight through propagation for the  
22 TM polarization.

1 In practice, considerable prior art effort has been devoted to solving the PBS problem for  
2 tunable filters by using two mode interference and Ti-indiffused/proton exchanged waveguide  
3 combinations. Although polarization extinction ratios  $> 20$  dB have been reported, the techniques  
4 to achieve them are complicated and reproducibility has been a major problem. Due to difficulties  
5 with the integrated PBSs, some AOTF demonstrations have utilized bulk PBSs external to the  
6  $\text{LiNbO}_3$  substrate in which the acoustooptic interaction takes place.

7 Simpler 2-port filters of the present invention, designed using the same principles as the  
8 4-port devices, are illustrated in Figs. 6 and 7. These 2-port filters are designed to transmit a  
9 selected wavelength channel and block all others. In the 2-port filters, two 3-port Y-branches  
10 replace the two 4-port beam splitters employed in the designs of Figs. 4 and 5. If the 3-port  
11 branches are symmetric, the splitting ratios will be 50% for both polarizations and the condition  
12 of eq. (15) is automatically satisfied. As with the 4-port filters of the present invention, the optical  
13 path difference for the waveguides between the beam splitters for both polarizations is a half-  
14 wavelength, or odd integral multiples thereof, and the relative positions of the polarization  
15 coupling regions in the two waveguides are displaced in the propagation direction by half the  
16 spatial period of the perturbation responsible for the coupling.

17